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MRL-TN-478

INITIAL ACCELERATION FOR ELECTROMAGNETIC LAUNCHERS: A FEASIBILITY STUDY ON CHEMICAL PROPELLANTS

M.J. Chung

Approved for Public Release

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This report discusses the feasibility of using conventional gun propellants to accelerate projectiles to velocities of about 1000 m/s before the pulse of electromagnetic energy is applied. A square-bore barrel is desirable to ensure a suitable interface between the barrel using chemical propellant and the rails of the electromagnetic propulsion device.

Calculations show that minute amounts of an ionizing salt may be added to the propellant to enhance the conductivity of the plasma produced between the conducting rails and behind the projectile.

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Stored electromagnetic energy has been used at MRL and elsewhere to accelerate projectiles to ultra-high velocities. This novel method of acceleration suffers from the disadvantage that large currents could damage the conducting rails or the projectile particularly when the latter is at rest or moving slowly.

This report discusses the feasibility of using conventional gun propellants to accelerate projectiles to velocities of about 1000 m/s before the pulse of electromagnetic energy is applied. A square-bore barrel is desirable to ensure a suitable interface between the barrel using chemical propellant and the rails of the electromagnetic propulsion device.

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INITIAL ACCELERATION FOR ELECTROMAGNETIC LAUNCHERS:

A FEASIBILITY STUDY ON CHEMICAL PROPELLANTS

1. INTRODUCTION

Materials Research Laboratories is undertaking a study into the feasibility of using electromagnetic methods for propelling small projectiles along two copper conducting rails. Acceleration is caused by forces arising from high currents flowing across magnetic fields.

Experimental work carried out at these Laboratories [1] indicates that a large fraction of the energy is required to initiate motion of the projectile. The sudden application of large amounts of electrical energy to the stationary projectile may lead to excessive wear and physical damage to the 'breech' of the electromagnetic guns rails and a reduction in the stored energy of the electromagnetic system. If this projectile can be initially accelerated by some means other than stored electromagnetic energy, more energy is then available to sustain the projectile's acceleration along the rails of the device, leading to higher muzzle velocities.

It may be feasible to use a conventional gun propellant to impart an initial velocity to the projectile by means of a special gun interfaced with the copper conduction rails of the electromagnetic system. The propellant may also be a suitable means to enhance the conduction properties of the plasma produced between the rails and behind the projectile.

The realization of this conventional gun and the interfacing aspect of the two devices will be examined in this Note.

2. PROPELLANT DEVICE

For efficient use of the electromagnetic energy to accelerate the projectile, a convenient shape for the bore of a rail gun is a square [2].

For this conceptual study, a hypothetical cubic projectile of mass 1 gram, of side 1 cm was assumed to attain a nominal velocity of (1000 ± 20) m/s from the conventional chemical propellant. These values are taken so that a quantitative discussion is possible in subsequent sections.

2.1 Ordnance

The geometric size and shape of the projectile imposes a major constraint on the type of gun barrel suitable to achieve a muzzle velocity of 1000 m/s. The barrel must ensure there is no change in the orientation of the projectile as it is accelerated along the barrel and passes to the conducting rails of the electromagnetic gun. Two methods may be available to comply with this constraint:

1. Construction of a special gun with a square bore whose physical dimensions are 1 cm x 1 cm.

and

2. The keying of a smooth bore gun and using a sabot round containing the cubic projectile.

Several small arms barrels of suitable dimensions which may be altered to contain the cubical projectile are available to the Australian services. They are the 0.5 in. Browning machine gun, 20 mm and 30 mm cannon. The 0.50 calibre Browning machine gun barrels are produced at the Lithgow Small Arms Factory and the 30 mm Defa barrels were produced at the Ordnance Factory, Maribyrnong. The 20 mm barrels are imported. For reasons of availability, the Browning barrel, breech and cartridge would be most suitable for this application. The Browning barrel with a 1 cm square to scale is shown in Figure I-1.

2.2 Square Bore Barrel

2.2.1 Machined Barrel

The physical dimensions of a 0.50 calibre machine gun [3] barrel allows a 1 cm x 1 cm square bore to be machined in a solid barrel by means of a broaching tool. The length of the machine gun barrel [3] is 1.02 m (3.35 ft) and the broaching tool would have to be specially constructed for this application. Figure I-2 indicates the proposed barrel at a section AA referred to in Figure I-1.

The magnitude of stress, concentrated at the corners of a square bore is not known; a small chamfer or radius will tend to relieve these stresses, however, it is expected that cracking in the corners would occur after a number of firings. These engineering investigations are beyond the scope of this Note. The yield stress of the Browning machine gun barrel is 630 MPa [4], 0.2% proof stress. Stress calculations [5] in Appendix I

indicate that the standard machine gun barrel may contain breech pressures of 674.9 MPa. If the barrel is broached and the diagonal of the square bore is considered as an equivalent diameter of a circular bore, the maximum breech pressure the barrel may contain and produce a tangential stress in the barrel's material which is within the yield stress of the metal, is 652.4 MPa. These pressures only apply to the sleeved section of the barrel. These Laboratories do not have a broaching machine [6] which can cope with the length of the barrel and consequently the specially constructed barrel cannot be made at MRL. The Ordnance Factory traditionally works with larger calibre weapons and recommended an approach be made to the Lithgow Small Arms Factory. This Factory may have the capabilities for the construction of this barrel [7].

2.2.2 Fabricated Barrel

A fabricated barrel may be constructed at MRL using four machined rods, matching them together and binding the structure with a heat shrunk steel outer tube [6]. This structure eliminates stress concentrations in the corners of the bore. This fabricated barrel is shown in Figure I-3. To contain pressures of 471.6 MPa, calculations shown in Appendix I indicate a steel tube of yield stress 630 MPa 0.2% proof stress and of thickness 1.80 cm (0.71 in.) is required. The tube is required to exert a shrinkage pressure of 23.96 MPa (3475 psi) to enable action stresses in the inner fibre of the tube to equal that of the elastic limit of the tube. This fabricated barrel should be matched to the 0.5 in. machine gun's breech [3]. Engineering details of this fabricated barrel or other variants have not been considered in this Note.

2.2.3 Keyed Barrel

For construction convenience, a keyed bore may be preferable to a specially constructed square bore gun. The Browning machine gun barrel could be adapted by drilling the bore out to 1.61 cm (0.64 in.) and broaching 4 straight parallel grooves the length of the barrel. The grooves would be of similar dimensions to that of the standard spiral grooves of the 0.5 in. barrel's rifling. This proposed bore is shown in Figure I-4. The use of this barrel requires a sabot to contain the round. Calculations [5] shown in Appendix I indicate that this barrel can withstand breech pressures of 635.2 MPa. Appendix II describes a suitable design [8] for a sabot of Teflon. The use of a sabot adds an additional complication to the interfacing of the two systems. The sabot or its fragments would need to be captured prior to the entrance of the rail gun as it is expected that the sabot would interfere with the operation of the rail gun.

3. PROPELLANTS

A gun propellant produced in Australia which may be used for this purpose is the propellant AR2203 or a composite charge consisting of

AR5401/FNH025. The propellant AR2203 is used as the charge for 20 mm Hispano projectiles. The composite charge has been used experimentally in a smooth bore gun at MRL and has been suitably modelled [9]. Equations used to model the ballistics of the cubic projectile in the hybrid gun have been previously described [10] and are shown in Appendix III.

Results shown in Appendix III indicate that the optimum charge mass for maximum muzzle velocities of the order of 900 m/s for both proposed propellant charges is 8.2 g (0.018 lb.). Neither propellant can cause a 1 gram projectile to reach 1000 m/s. Calculations show that large amounts of the charge remains unburnt, indicating that for this particular gun, the charges are inefficient. Predicted maximum pressures are extremely low (approx. 30.9 MPa 2 ton/in^2) for the propellant device and because of the similarity between the propellants AR2204 and IMR4676, pressures comparable to those shown in Table III-1 would seem reasonable for this application. Because of this uncertainty, it would be necessary that test firings would proceed with low charge weights which could then be increased progressively according to pressure and velocity measurements until suitable muzzle velocities with reasonable maximum pressures were achieved.

McHenry's work [11] with small bore guns indicated that the standard deviation in the estimate of fired velocity was 2.3%. As similar methods of calculations have been used to examine the muzzle velocity of the cubic projectile, it seems reasonable to expect a similar standard deviation for this gun.

4. BLAST EFFECTS

The propellant device would need to be interfaced with the rail gun to ensure no changes in orientation of the cubic projectile. If design requirements of the project require the two devices to be separated, either for convenience or to enable sabot capture, the rail gun would be subjected to blast effects from the muzzle of the propellant device. Appendix IV indicates methods [12] to calculate blast effects for a barrel of smaller calibre (7.62 mm) and suggests that at a separation distance of 7.62 cm, a blast pressure of 0.35 MPa (3.5 atmospheres) exists for 89 μs.

Using the modified 0.50 calibre Browning barrel and the recommended propellant, it is expected that similar blast effects will be present.

5. SEEDED PROPELLANTS

Pressure and temperature levels present in the propellant gas would be sufficient to cause ionization of certain selected salts such as caesium chloride or sodium chloride. The addition of these salts to the propellant

would enhance an existing plasma behind the projectile and could exceed the minimum ion concentration necessary for suitable conduction in the plasma.

To produce an ion concentration of 10^{16} ions/m^3, Appendix V indicates that small amounts of alkali halide are required (3.9×10^{-5} g) and at these mass levels, performance of the propellant would not be degraded by any significant amount.

6. CONCLUSION

Changes in the orientation of the projectile are not desirable and to eliminate any such possibility, a square bore barrel, interlocked with the rail gun is preferred. The use of this barrel eliminates problems such as blast effects and sabot capture which would occur with the use of a keyed barrel.

For this device, propellant AR2203 is the more suitable than AR5401/FNH025. Muzzle velocities of 900 m/s with a standard deviation of 2.3% are to be expected. This muzzle velocity is less than the specified 1000 m/s but may be suitable for this purpose. Because of the uncertainty in the modelling of the ballistics of this propellant in the experimental gun, test firings should proceed with lower charge weights which may be altered progressively according to pressure and velocity measurements.

Calculations have shown that minute amounts of alkali salt 3.9×10^{-5} g) are necessary to produce an ion concentration of 10^{16} ions/m^3.

7. RECOMMENDATIONS

1. A fabricated square bore barrel of material of yield strength 630 MPa, length 1.02 m, using a 0.50 calibre breech and cartridge could contain propellant gas pressures required to produce muzzle velocities of 900 m/s with a 1 gram projectile.

2. Propellant AR2203 can be used in the fabricated gun to achieve muzzle velocities of 900 m/s with the 1 gram projectile.

3. Seeding of the propellant to enhance the plasma behind the projectile may not be necessary, ions present in the propellant gas should be sufficient to produce an initial ion concentration of 10^{16} ions/m^3.

4. Further work on the use of conventional propellants requires detailed study in the following areas:

a. engineering of the fabricated barrel

b. interfacing aspects

c. experimental measurements of the velocity-pressure data of the conventional gun.

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APPENDIX I

STRESSES IN SIMPLE HOLLOW CYLINDERS

The tangential stress S_T, a distance r from the axis of a cylinder may be expressed [5] as:

$$S_T = \frac{(P_o R_o^2 - P_1 R_1^2) r^2 - R_o^2 R_1^2 (P_1 - P_o)}{(R_1^2 - R_o^2) r^2} \qquad (1)$$

where P_o is the unit pressure acting on the interior of the cylinder

P_1 is the unit pressure acting on the exterior of the cylinder

R_o is the internal radius of the cylinder, and

R_1 is the external radius of the cylinder.

Interior Pressures only:

For interior pressures acting on the cylinder, the tangential stress would be expected to be greatest at the inside surface of the cylinder and decrease to a minimum at $r = R_1$. From equation (1), with $P_1 = 0$, the tangential stress due to interior pressures alone may be expressed as:

$$S_T = \frac{P_o (R_o^2 r^2 + R_o^2 R_1^2)}{(R_1^2 - R_o^2) r^2} \qquad (2)$$

Exterior Pressures only:

This situation occurs when the barrel of a gun is not subjected to the interior pressures of the propellant gas. For this case $P_o = 0$ and the tangential stress may be derived from equation (1) and expressed as:

$$S_T = \frac{P_1 (R_1^2 r^2 + R_o^2 R_1^2)}{(R_o^2 - R_1^2) r^2} \qquad (3)$$

For a layered compound cylinder, produced by heat shrinking methods, it is assumed that the inner fibre of the internal layer may be stressed safely to the material's elastic limit by in-action pressures.

The contact pressure P_c, between the two cylinders of a layered system may be expressed [5] as:

$$P_c = \frac{E\delta}{2R_1^{\,3}} \quad \frac{(R_2^{\,2}-R_1^{\,2})(R_1^{\,2}-R_o^{\,2})}{(R_2^{\,2}-R_1^{\,2})} \qquad (4)$$

here $R_o < R_1 < R_2$

where E is Young's Modulus of the cylinder's material (assumed similar),

δ is the deformation of the cylinders after heat treatment, and

R are the internal, interface and external radii respectively.

A. Calculation of pressures in the rifled 0.50 calibre Browning Barrel

At the section of the barrel, composed of a liner and tube shown in Figure I-1, the radii are:

Inner liner radius R_o 0.65 cm (0.2545 in)

Inner tube radius R_1 0.95 cm (0.3745 in)

Outer tube radius R_2 2.75 cm (1.0830 in)

and,

Deformation of heat shrunk tube δ 6.35×10^{-4} cm

The elastic limit and Young's Modulus of the material of the tube and liner are taken as 630 and 200000 MPa respectively. When the barrel is in action, it is assumed that the inner fibre of the liner will be stressed tangentially to the elastic limit by interior pressures and that the external pressures on the barrel are zero. The contact pressure may be calculated from equation (4) as 33.2 MPa and the compressive stress at the inner fibre of the inner liner due to the contact pressure may be calculated from equation (3) as 124.8 MPa. The interior pressure this barrel may contain and stress the inner fibre of the liner to its elastic limit, may be calculated from equation (2) as 674.9 MPa.

B. Approximations of pressures in a square bored barrel

Broaching of a solid 0.50 calibre barrel does not alter the physical dimensions of the outer tube. The diagonal of the square bore is 1.414 cm, to make some allowance for stress concentrations existing in the corners of the bore, a diagonal of 1.514 cm will be used as an equivalent diameter for the inner liner.

For a square bore, at the same section of the barrel shown in Figure I-2 the radii become:

equivalent inner liner radius R_o 0.75 cm (0.2980 in)

inner tube radius R_1 0.95 cm (0.3745 in)

outer tube radius R_2 2.75 cm (1.0830 in)

For a deformation of 6.35×10^{-4} cm, a contact pressure of 23.9 MPa exists between the liner and the tube. This contact pressure produces a compressive stress of 127.2 MPa at a radius of 0.75 cm. The interior pressure the compound cylinder is of the order of 652.4 MPa.

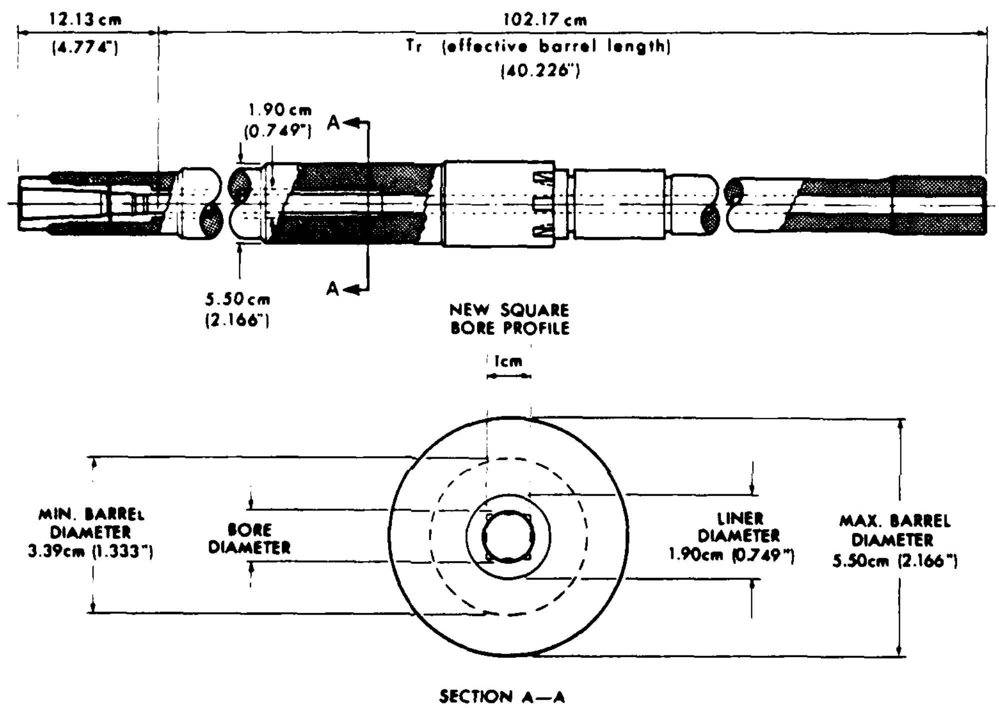
In the event that cracking occurs in the corners of the broached liner, no additional strength is gained from the liner. The containment of action pressures rests solely with the outer tube. The pressure magnitude this tube may contain, then becomes similar to that of a Fabricated barrel, described below.

C. Fabricated Barrel

The outer tube of the existing 0.50 calibre barrel is of suitable dimensions to contain the machined sections. Dimensions shown in Figure I-3 indicate a 2.4 mm surface is available for suitable locating of these sections. These sections will not assist in the containment of barrel pressures. The outer tube is expected to be heat shrunk around the sections to produce a contact pressure similar to that of the square bore barrel, that is, 23.96 MPa. The inner fibre stress for these conditions may be calculated from equation (2) as 30.5 MPa. To ensure that the inner fibre is not stressed beyond 630 MPa during action, equation (2) indicates that the fabricated barrel may contain pressures of 471.6 MPa.

D. Approximations of pressure in a keyed bore

Similarly, the pressure in a 0.50 calibre barrel, keyed to accommodate a sabot round may be approximated by considering the pressure at a radial distance of 0.82 cm (0.323 in). A cross section of this keyed barrel is shown in Figure I-4. For tube material of elastic limit 630 MPa, the interior tube pressure is found to be 635.2 MPa.



Sectioned 0.50 calibre barrel

FIG. I-1

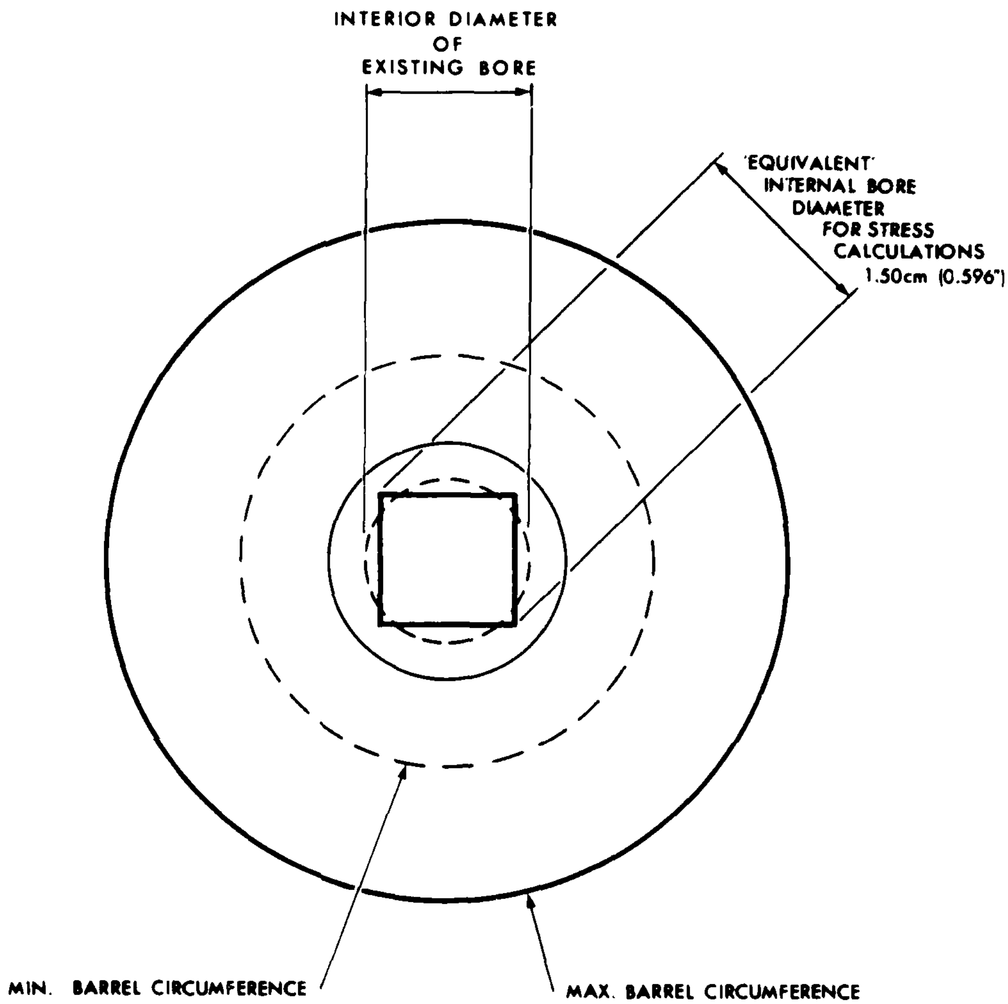


FIG. I-2 Square Bore at section AA

i. One centimeter cube drawn to scale on section AA of Figure I-1.

ii. The diagonal of the cube represents an equivalent inner liner diameter for stress calculations.

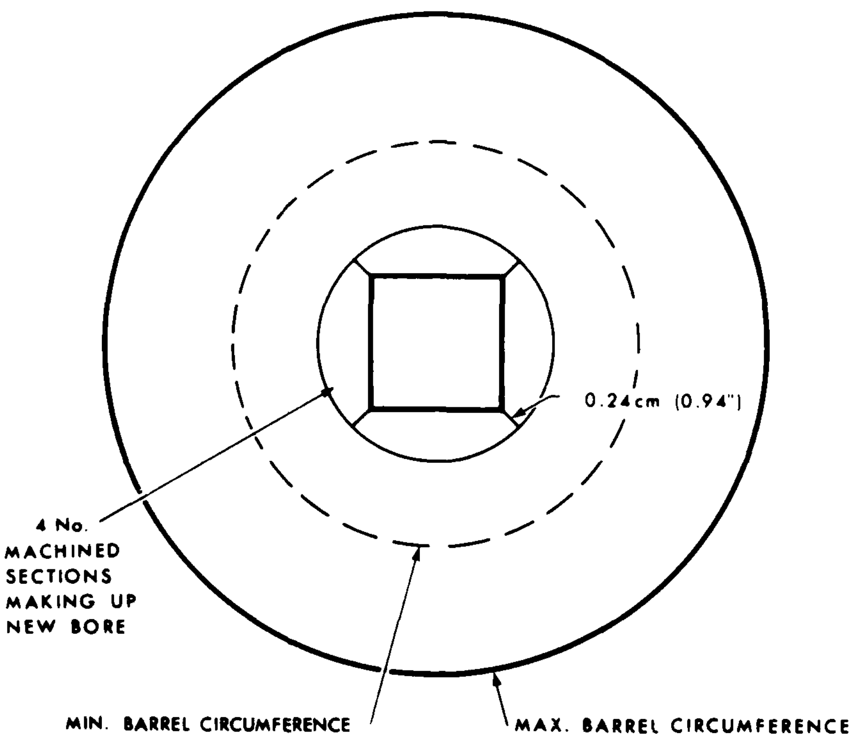


FIG. I-3 Fabricated bore at section AA

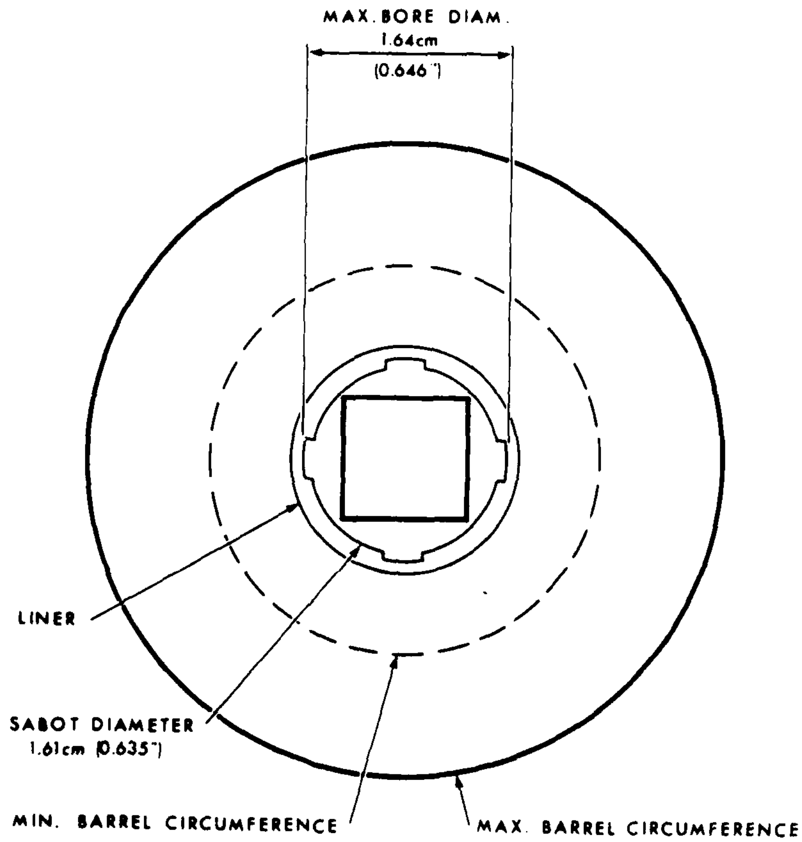


FIG. I-4 Keyed bore at section AA

The bore diameter represents an equivalent inner radius for stress calculations.

APPENDIX II

DESIGN OF A SABOT TO CONTAIN A CUBIC PROJECTILE

Using the same method of analysis described in [8] for a cup sabot, the expected method of failure will be the shearing out of a part of the sabot base of the same dimensions as the projectile's base. The forces acting on the sabot section shown in Figure II-1 may be expressed [8] as:

$$Pd^2 - \tau 4dt = (M_p + \rho d^2 t)a \tag{1}$$

where P is the pressure acting on the base of the sabot,

d is the dimension of the cube,

t is the thickness of the sabot base,

τ is the stress produced by shearing action in the sabot,

M_p is the mass of the projectile,

ρ is the density of the sabot's material,

and a is the acceleration of the sabot and projectile.

The thickness t may be derived as:

$$t = \frac{Pd^2 - M_p a}{\rho d^2 a + 4\tau d} \tag{2}$$

For the sabot to be structurally sound, the shear stress τ experienced in the sabot material due to acceleration forces on the cup must be less than or equal to the shear strength of the material. Equation (2) describes the minimum thickness of the sabot's base for a material of shear strength τ. For aerodynamic stability, the relationship between the sabot's dimensions and the projectile is given [8] by:

$$K = \frac{L-t}{d} \quad \text{where } 0.5 < K < 1.0$$

from which it follows:

$$0.5\, d+t < L < d+t \tag{3}$$

where L is the length of the sabot cup.

For a teflon sabot subjected to gun conditions [11] indicated in Table II-1, from equation (2), the minimum thickness of the sabot's base is 2.5 cm. For minimum aerodynamic stability, the length of the sabot can be calculated from equation (3) as 3.0 cm.

Table II-1

maximum pressure(1)	P	8.2×10^9 Pa
corresponding acceleration(1)	a	5.3×10^7 m/s
cube dimension	d	10^{-2} m
projectile mass	M_p	10^{-3} g
density of teflon(2)	ρ	2297.4 kg/m
tensile strength of teflon(2)	σ	0.9×10^9 Pa
shear strength of teflon		$\tau \simeq 0.5\sigma$

1. Obtained from reference [11].

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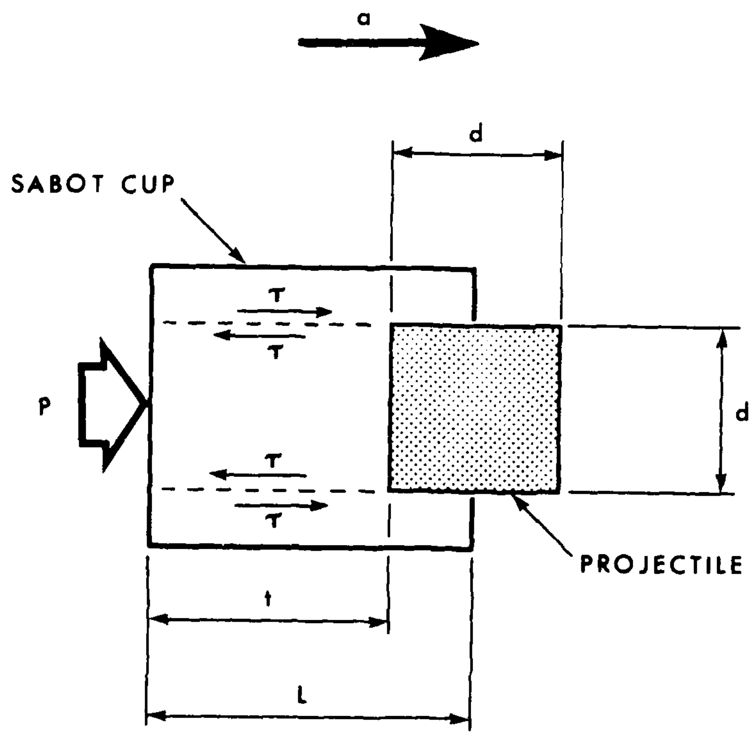


FIG. II-1 Simple cup sabot containing a cubic projectile

APPENDIX III

INTERIOR BALLISTICS OF A CUBIC PROJECTILE

The equations used to describe the cubic projectile in the barrels considered in this Note are based on Goldie's method of interior ballistics [10]. These equations are:

1. The energy equation

$$AP(x+1) - 27.68\ Pcz\ (b - \frac{1}{\delta}) + (\gamma-1) \int_{o}^{x} APdx = Fcz$$

2. The rate of burning of the propellant

$$D\frac{df}{dt} = - .001\beta P^{\alpha}$$

3. The form function of the propellant

$$Z = (1 - f)(1 + \theta f)$$

4. The motion of the projectile

$$\frac{VdV}{dx} = 1.867 \times 10^{-4} \frac{APg}{m}$$

where $W_1 = W + \frac{c}{3}$ and;

A is related to the area of the cross-section of the gun bore,

b is the co-volume of the propellant gas,

c is the charge weight of the propellant,

D is the ballistic size of the propellant,

F is the force constant of the propellant,

f is the fraction of D remaining unburnt at a given time t,

g is the acceleration due to gravity,

l is the length between the base of the projectile and the propellant,

P is the mean gas pressure in the volume behind the projectile at a given time t,

P_o shot start pressure,

t is time in milliseconds,

V is the velocity of the projectile,

W is the projectile mass,

z is the fraction of the charge burnt,

x is the projectile travel in time t,

Tr is the shot travel to muzzle,

α is the burning rate exponent, taken here as unity

β is the burning rate constant of the propellant,

δ is the grain density of the propellant,

γ is the ratio of the specific heats of the propellant,

and θ is the form function of the propellant.

The pressures described in these equations represent the mean gas pressure in the volume behind the projectile. It is assumed that these pressures act uniformly over the projectile's section. The mass of the projectile used in this application is small (1 g), for the charge weights being considered to propel this projectile, the charge to shot weight ratio (c/W) is 8.2. This ratio is considerably greater than that ratio of 0.45 which Goldie [10] originally considered.

Terms involving c/W arise from the inertia of the moving gas in the gun barrel. In principle, Goldie's method is applicable to all values of c/W, but in practice, calculations are limited by the effects in the pressure gradient terms [11]. An expression deduced by McHenry [11] for the inertia pressure gradient which is more suitable for use in Goldie's method of ballistics for the case of high c/W ratios is:

$$\left(1 + \frac{c}{3W} - 0.00257 \left(\frac{c}{W}\right)^2\right)$$

instead of

$$\left(1 + \frac{c}{3W}\right)$$

This alteration has been made to the computer program used in the mathematical modelling of the propellant gun and a comparison between

theoretical and experimental results for a 0.50 calibre Browning gun using propellant IMR 4676, Lot Ma 838 is shown in Table III-1.

The Australian AR2203 was designed for the 20 mm Hispano and the thermochemical constants are roughly similar to IMR4676, the major difference being the ballistic size of the propellant. Propellant AR2203 may be expected to provide similar performance as the IMR4676 propellant in the 0.50 calibre guns. Calculations show that AR2203 requires a burning rate constant β of 1.21 to provide similar performance as the IMR4676. The results of these calculations are shown in Table III-2.

Using the thermochemical constants for AR2203 and the predicted burning rate constant $\beta = 1.21$, the ballistics of the cubical projectile has been calculated for the three suggested gun barrels. These results are shown in Table III-3. For comparison with another type of propellant, the ballistics of the same gun, using a composite change of AR5401/FNH025 is shown in Table III-4.

TABLE III-1

Thermochemical constants of IMR4676, units are expressed in a form convenient for ballistic calculations

T_o (assumed)	3079 K
F 1843.5 ton/in^2 per lb/in^3	
γ	1.239
δ	1.622 g/cm^3
η	0.940 cm^3/g
θ	0
D	0.0134 in
Bore diameter	0.507 in
Tr	4.67 ft
Cap	2.190 in^3
W	0.0199 lb
c	0.06286 lb
P_o (assumed)	0.5 ton/in^2
β_1	0.787 in/s per ton/in^2
$\frac{c}{W}$	3.16
P_m calculated	15.8 ton/in^2
$V_{calculated}$	6426 ft/s
V_{fired}	5690 ft/s

TABLE III-2

Thermochemical constants of the Propellant AR2203[1] in 0.5" Browning gun. The units are expressed in a form convenient for calculations.

T_o	3079 K
F 1843.5 ton/in^2 per lb/in^3	
η	0.966 cm^3/g
δ	1.625 g/cm^3
γ	1.241
θ	0
D	0.022 in
c	0.06286 lb
Cap	2.19 in^3
Bore diameter	0.507 in
Tr	4.67 ft
W	0.019 lb
Pt	15.8 ton/in^2
P_o	0.5 ton/in^2
β calculated	1.21 in/s per ton/in^2
$V_{calculated}$	6487 ft/s

1. Thermochemical Constants provided by Combustion and Explosives Group, D.R.C.S.

TABLE III-3

Thermochemical constants for the propellant AR2203

in the three suggested gun barrels

Constant	Units	Circular Bore Diameter = 0.50"				Square Bore Diameter = 0.444"	Keyed Bore Diameter = 0.646"
T_o	K	3079					
F	ton/in^2 per lb/in^3	1843.5					
η	cm^3/g	0.966					
δ	g/cm^3	1.625					
γ		1.241					
θ		0					
D	inch	0.022					
c	lb	0.018	0.02	0.025	0.031	0.018	0.018
Cap	inch^3	1.08					
Tr	ft	3.35					
W	lb	0.0022				0.0022	0.0088*
$P_{m_{calculated}}$	ton/in^2	1.85	1.89	1.99	1.76	1.98	1.87
P_o	ton/in^2	0.50					
β	in/s per ton/in^2	1.21					
$V_{calculated}$	ft/s	2745	2745	2686	2393	2953	2093
f		0.87	0.87	0.88	0.88	0.876	0.875

* projectile 1 g plus 3 g sabot

TABLE III-4

Thermochemical constants of the composite charge AR5401/FNH025 is the three suggested gun barrels

		Circular Bore Diameter = 0.5"		Square Bore Diameter = 0.444"	Keyed Bore Diameter = 0.646"
T_c	K	2585			
F	ton/in^2 per lb/in^3	1688.8			
η	cm^3/g	0.974			
δ	g/cm^3	1.593			
γ		1.26			
θ		0.27			
D	inch	0.036			
c	lb	0.018	0.025	0.018	0.018
Cap	$inch^3$	1.08			
T_r	ft	3.35			
W	lb	0.0022		0.0022	0.0088*
$P_{m_{calculated}}$	ton/in^2	1.80	1.92	1.91	1.83
P_o	ton/in^2	0.5	0.5		
β	in/s per ton/in^2	1.578			
$V_{calculated}$	ft/s	2587	2587	2795	1990
f	0.876 0.876	0.875		0.875	

* 1 g projectile plus 3 g sabot

APPENDIX IV

MUZZLE BLAST EFFECTS

The blast effects forward of the muzzle of a gun are a function of the distance R from the source of blast, the duration of the blast phase τ^1 and an effective calibre C^1. The effective calibre varies with azimuth angle θ and a distribution factor D_f. This relationship is expressed by the equation:

$$\frac{C^1}{C} = D_f \cos\theta + (1 - f^2 \sin^2\theta)^{1/2} \qquad (1)$$

where C^1 is the effective calibre of the gun,

C is the calibre of the gun,

θ is the azimuth angle subtended at the muzzle,

and D_f is a distribution factor.

For a spherical charge, D_f is interpretated as the fraction of the charge radius of the detonation point from the centre. By analogy, the distribution factor for a gun barrel is taken as the fraction of the barrel's radius of the muzzle blast point from the change centre. For small calibre guns, the muzzle blast point is expected to be central, hence $D_f = o$.

For a point, forward of the muzzle and situated axially, $\theta = o$ and equation (1) becomes:

$$\frac{C^1}{C} = 1$$

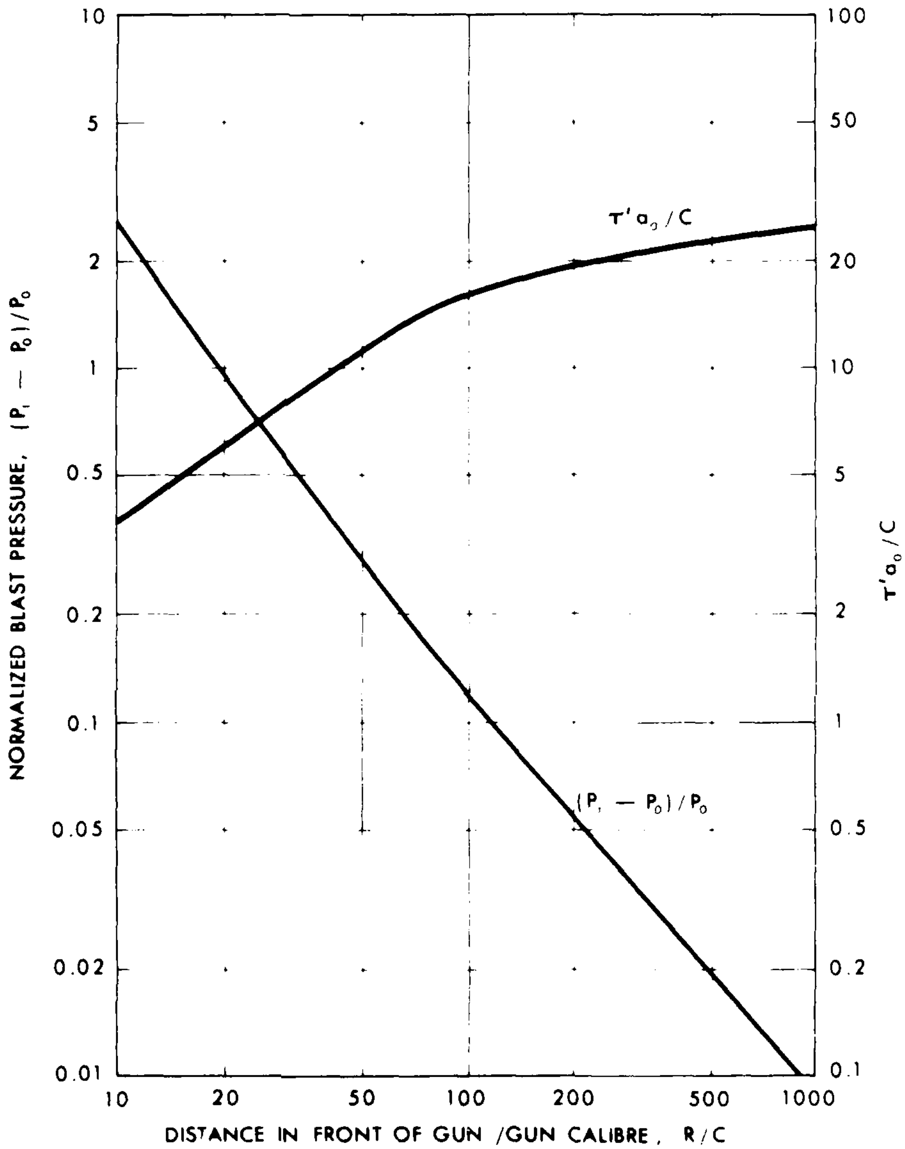
Using curves [12] shown in Figure IV-1 for a 7.62 mm rifle, for R/C^1 values of 10, 20 and 50, the pressure behind the blast front P_1 and duration τ^1 of the pressure pulse is shown in Table IV-1.

TABLE IV-1

$\frac{R}{C}$	R inches	$\frac{P_1 - P_o}{P_o}$	$\frac{P_1}{P_o}$	P_1 atmospheres	$\frac{\tau^1 a_o}{C}$	τ^1 μs
10	3 (7.62 cm)	2.5	3.5	3.5 (.35 MPa)	0.4	89
20	6 (15.24 cm)	0.9	1.9	1.9 (.19 MPa)	0.7	155
50	15 (38.1 cm)	0.3	1.3	1.3 (.13 MPa)	0.85	189

a_o is the speed of sound in the atmosphere (34240 cm/s)

P_o is the ambient air pressure (.10 MPa)



NORMALIZED BLAST PRESSURE, $(P_1 - P_0)/P_0$
$\tau' a_0 / C$
$(P_1 - P_0)/P_0$
DISTANCE IN FRONT OF GUN /GUN CALIBRE, R/C
10
5
2
1
0.5
0.2
0.1
0.05
0.02
0.01
100
50
20
10
5
2
1
0.5
0.2
0.1
10
20
50
100
200
500
1000

FIG. IV-1

APPENDIX V

SEEDED PROPELLANTS

1. Introduction

Partial ionization of the propellant gas at the elevated pressures and temperatures will be produced on combustion of the propellant. This natural ionization is probably insufficient to permit unimpeded electrical flow; the possibility of adding some 'seed' to enhance the ionization has to be considered. The enhancement can probably be achieved by the addition of small amounts of alkali halide. Specification of a suitable ion concentration would enable the mass of the seed to be calculated.

Further ionization of the propellant gas is expected to occur in the propellant gas by means of Townsend's breakdown criteria [14] between the rails of the electromagnetic launcher. This process may lead to the establishment of a fully ionized gas behind the projectile.

2. Ion Concentration

At temperatures and pressures experienced in the propellant gas, it is expected that an alkali halide would produce a lightly ionized plasma. A lightly ionized plasma is one that contains 10^{12} ions/m^3 to 10^{16} ions/m^3 [14]. To ensure the highest electrical conduction in the propellant gas, an initial concentration of 10^{16} ions/m^3 would be desirable.

3. Mass of Alkali Halide required to meet Design Criteria

Let M_a be the mass of an additive salt, ionization potential V, added to the propellant of mass M_p such that the total mass M_T is given by:

$$M_T = M_a + M_p \tag{1}$$

The fraction x of this salt, ionized under conditions of partial pressure h and temperature T is given by Saha's equation [16]

$$\log_{10}\left(\frac{x^2 h}{1-x^2}\right) = \frac{-5040V}{T} + \frac{5}{2}\log_{10} T - 3.61 \tag{2}$$

If the salt and the propellant gas are uniformly distributed throughout the system then the mass of the salt required to produce a particular plasma property for given temperatures and pressures may be determined in the following manner.

For a propellant device interfaced with the rail gun shown schematically in Figure V-1, the total volume V(t) at any time t after the projectile enters the rails is given by:

$$V(t) = V_1 + V_2(t)$$

where V_1 is the fixed volume of the gun and $V_2(t)$ is the volume between the interface and the projectile. For uniform distribution of the propellant gas, the mass of the gas M_V in volume $V_2(t)$ is given by:

$$M_V = \frac{M_T V_2(t)}{V(t)}$$

From equation (1), M_V may be expressed in terms of the propellant and additive masses:

$$\text{i.e.} \qquad M_V = \frac{V_2(t)}{V(t)} (M_p + M_a) \qquad (3)$$

The mass of the salt M_a, consists of ionized and non-ionized molecules, equation (3) may be written as:

$$M_V = M_p \frac{V_2(t)}{V(t)} + (1 - x) M_a \frac{V_2(t)}{V(t)} + xM_a \frac{V_2(t)}{V(t)} \qquad (4)$$

Where $(1-x)M_a V_2(t)/V(t)$ is the mass of non-ionized molecules and $xM_a V_2(t)/V(t)$ is the mass of ionized molecules. Only the ionized molecules can take part in the enhancement of the electrical conductive properties of the plasma and equation (4) indicates that a mass of $xM_a V_2(t)/V(t)$ of the additive is present in the railgun. From Avogadro's hypothesis, at standard temperature and pressure, this mass contains

$$2\frac{xM_a V_2(t) N_A}{V(t)S} \text{ ions,}$$

where N_A is Avogadro's number (i.e 6.023×10^{23}) and S is the gram molecular weight of alkali salt.

The ion concentration n_e in a volume $V_2(t)$ is given by:

$$n_e = \frac{x M_a N_A}{V(t)S}$$

from which the mass of the salt in grams is found to be:

$$M_a = \frac{n_e V(t)S}{x N_A} \qquad (5)$$

4. Application to the Rail Gun

For the square bore barrel, using propellant AR2203, the cubic projectile achieves a muzzle velocity of approximately 900 m/s. For these conditions, muzzle pressure is 58000.0 mm of Hg (7.66 MPa) and the temperature of the propellant gas is 2179 K. One microsecond after the cubic projectile has left the muzzle, the projectile has travelled 0.09 cm. The total volume occupied by the propellant gas is thus $V(t) = 1.2 \times 10^{-4}\ m^3$. Taking the chloride salts of each of sodium, potassium and caesium, the maximum masses required to produce an ion concentration of 10^{16} ions/m^3 are shown in Table V-1.

It can be seen that if the required ion concentration is increased by a factor λ, the mass of seed should be increased by the same factor.

TABLE V-1

Alkali Salt	Mass required g	n_e ions/m^3
Sodium	3.9×10^{-5}	10^{16}
Potassium	7.9×10^{-6}	10^{16}
Caesium	8.13×10^{-6}	10^{16}

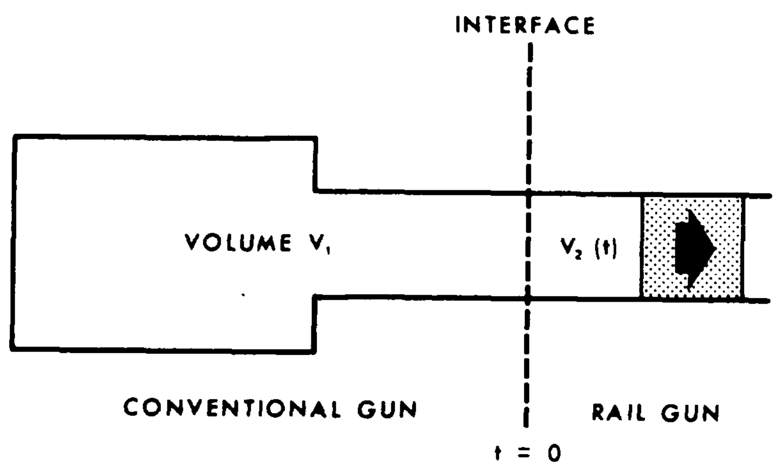


FIG. V-1

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